AFRL-OSR-VA-TR-2015-0117

Light control and image transmission through photonic lattices with engineered

Zhigang Chen
SAN FRANCISCO STATE UNIVERSITY

05/05/2015
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTB
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
21-05-2015

2. REPORT TYPE
Final Performance

3. DATES COVERED *(From - To)*
01-04-2012 to 31-03-2015

4. TITLE AND SUBTITLE
Light control and image transmission through photonic lattices with engineered coupling

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-12-1-0111

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Zhigang Chen

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
SAN FRANCISCO STATE UNIVERSITY
1600 HOLLOWAY AVE BUILDING NAD ROOM 358C
SAN FRANCISCO, CA 941321722 US

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The objective of this project is to develop research programs in photonic lattices that are at the frontier of nonlinear optics/photonics for fundamental understandings in scientific knowledge as well as for possible applications of direct interest to the Air Force. The proposed studies include mainly beam control in engineered photonic lattices, Tamm and Shockley-like edge states and topological surface states in 2D honey-comb lattices (photonic graphene), and light localization and transport in disordered lattices. Apart from these proposed studies, the project made additional efforts on design and control of self-accelerating beams and nonlinear enhanced transmission in synthetic colloidal nanosuspensions. These studies will advance the knowledge in several interdisciplinary areas such as nonlinear optics, condensed matter physics, atmospheric sciences, and will also have many application potentials.

15. SUBJECT TERMS
Light Propagation, Nonlinear Crystals, Nonlinear Schrodinger Equation

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU		Zhigang Chen

19b. TELEPHONE NUMBER *(Include area code)*
415-338-3876

FINAL PERFORMANCE REPORT (APRIL 2015)

Zhigang Chen
San Francisco State University
zhigang@sfsu.edu

Title: Light Control and Image Transmission through Photonic Lattices with Engineered Coupling
Grant #: AFOSR # FA9550-12-1-0111
Program Manager: Dr. Arje Nachman
Reporting Period: APRIL 2012 - MARCH 2015

Abstract:

The objective of this project is to develop research programs in photonic lattices that are at the frontier of nonlinear optics/photonics for fundamental understandings in scientific knowledge as well as for possible applications of direct interest to the Air Force. The proposed studies include mainly beam control in engineered photonic lattices, Tamm and Shockley-like edge states and topological surface states in 2D honey-comb lattices ("photonic graphene"), and light localization and transport in disordered lattices. Apart from these proposed studies, the project made additional efforts on design and control of self-accelerating beams and nonlinear enhanced transmission in synthetic colloidal nanosuspensions. These studies will advance the knowledge in several interdisciplinary areas such as nonlinear optics, condensed matter physics, atmospheric sciences, and will also have many application potentials.

In this project, the optical induction technique has been employed to establish various specially designed photonic structures as a workbench for investigating some fundamental wave phenomena. These include, for example, image transmission through periodic media based on light tunneling inhibition, nontrivial surface (edge) states in honeycomb lattices, and accelerating diffraction-free beams and optical analog of Wannier–Stark beams in engineered photonic lattices. Although performed in a simple optical setting of reconfigurable photonic structures, much of our proposed work will have direct impact on other areas of sciences, ranging from solid state physics to atom physics such as Bose-Einstein condensates trapped in periodic potentials. As an example, the electronic edge states were known for decades, but such fundamental phenomena have recently attracted growing interest in optics that has led to the successful demonstration of photonic topological insulators. Indeed, this project shows that there is much potential to use optical systems as photonic simulators for studying complex classical and quantum phenomena.

Our previous work on nonlinear optics/photonics research was supported by a research grant from AFOSR (#FA9550-09-1-0474; Point of contact: Dr. Nachman), which ended in November, 2011. Earlier progress and success has been detailed in the final technical report submitted for that project, and has also been presented at the annual workshops on Nonlinear Optics organized by Dr. Nachman. This past 3-year contract (#FA9550-12-1-0111; Point of contact: Dr. Nachman, AFOSR/RSE) started in April 2012. During the three project years, the PI's group published about 40 referred papers that credited AFOSR, and about a dozen students at SFSU have participated in this funded project. Our work has been featured in *Optics & Photonic News* as one of the major

breakthroughs in optics of the year, has been cited frequently in literature. The results have also been presented in several invited and contributed talks at leading professional meetings and workshops. Here, we provide a summary report for our accomplishments.

Highlight of Major Efforts and Accomplishments:

In the last three year, we have successfully demonstrated several novel phenomena related to spatial beam dynamics and control of light in photonic bandgap structures, which led to high-level publications in prestigious journals. These include for example eliminating soliton transverse instability in one-dimensional lattices, inducing deep penetration and transparency in highly scattering media, controlling self-accelerating beams in free-space as well as in photonic lattices, and unveiling unconventional edge states in photonic graphene. In particular, we observed new edge states in zigzag and bearded edges of photonic graphene (published in *Nature Materials*), deep penetration of light through scattering media (published in *Physics Review Letters* and *Nano Letters*, and featured in *Nature Photonics* and *Physics*), and large-bending angle nonparaxial accelerating beams along curved trajectories (reported in a number of news media as well as featured in PRL cover and *Optics and Photonics News*). We are happy to report that we have made significant progress in this funded project with about 40 scientific research papers published in top-rated journals. (See attached list of publications that acknowledged the support from AFOSR). In addition, several students have actively involved and contributed significantly in this project, through which they were also trained in scientific areas of interest to Air Force. Close collaborations have been maintained with other principal investigators currently supported by AFOSR including Profs. Christodoulides, Ablowitz, and Yang. The following is a brief summary of our major accomplishments.

1. Edge states in photonic graphene:

   We developed a simple technique to optical induce 'photonic graphene' lattices and to observe edge states in these lattices. Specifically, we used the optical equivalent of graphene—a photonic honeycomb lattice—to study the edge states and their properties. We directly imaged the edge states on both the zigzag and bearded edges of this photonic graphene, measured their dispersion properties, and most importantly, found a new type of edge state: one residing on the bearded edge that has never been predicted or observed. Our work led to a number of subsequent discoveries in "photonic graphene" including the demonstration of optical topological insulator.

2. Wannier–Stark beams and accelerating diffractionless beams in photonic lattices.

   We generated optical beams analogous to the Wannier–Stark states in semiconductor superlattices and observe that the two main lobes of the WS beams self-bend (accelerate) along two opposite trajectories in a uniform one dimensional photonic lattice. We also showed that only a unique class of z-dependent lattices can support a true accelerating diffractionless beam. Accelerating lattice solitons, autofocusing beams and accelerating bullets in optical lattices are systematically examined.

3. Deep penetration of light needles through highly scattering media

   We have demonstrated two types of soft-matter systems with tunable optical nonlinearities - the dielectric and metallic colloidal suspensions. In both systems, we can alter at will the nonlinear light-matter interactions in order to overcome the effects of diffraction and scattering, hence achieving deep penetration of light needle through the colloid.

4. Linear and nonlinear nonparaxial self-accelerating beams

   We studied linear and nonlinear self-accelerating beams propagating along circular trajectories beyond the paraxial approximation. Such nonparaxial accelerating beams are exact solutions of the Helmholtz equation, preserving their shapes during propagation even under nonlinearity. We generate experimentally and observe directly these large-angle bending beams in colloidal suspensions of polystyrene nano-particles.

   In addition, we demonstrated both theoretically and experimentally nonparaxial Mathieu and Weber accelerating beams, generalizing the concept of previously found accelerating beams. We showed that such beams bend into large angles along circular, elliptical, or parabolic trajectories but still retain nondiffracting and self-healing capabilities. Not only do generalized nonparaxial accelerating beams open up many possibilities of beam engineering for applications, but the fundamental concept developed here can be applied to other linear wave systems in nature, ranging from electromagnetic and elastic waves to matter waves.
   This part of the work has merited a few papers published in *Optics Letters and Physical Review Letters.*

5. Elimination of transverse instability in stripe solitons by one-dimensional lattices

   In collaboration with AFOSR contractor Dr. J. Yang, we demonstrate theoretically and experimentally that the transverse instability of coherent soliton stripes can be greatly suppressed or totally eliminated when the soliton stripes propagate in a one-dimensional photonic lattice under self-defocusing nonlinearity. Both schemes and demonstrations were published in *Optics Letters.*

6. Self-accelerating Bessel-like optical beams along arbitrary trajectories

   In collaboration with AFOSR contractor Dr. Christodoulides, we proposed and experimentally demonstrated self-accelerating Bessel-like optical beams propagating along arbitrary trajectories in free space. With computer generated holography, such beams are designed to follow different controllable trajectories while their main lobe transverse profiles remain nearly invariant and symmetric. Examples include parabolic, snake-like, hyperbolic, hyperbolic secant, and even three-dimensional spiraling trajectories. The self-healing property of such beams is also demonstrated. This new class of optical beams can be considered as a hybrid between accelerating and non-accelerating nondiffracting beams that may find a variety of applications.

In addition, we demonstrated optical trapping and guiding micro-particles, aerosols and bacteria with a variety of specially designed optical beams, including rotating tweezers, optical bottles, and auto-focusing beams. This part of work has been published in several *Optics Letter* papers.

Interactions/Collaborations:

Participation of students and postdoc researchers in the proposed research

The P.I. has actively engaged students, especially underrepresented minorities, in his research. Currently, there are several undergraduate and M.S. graduate students including woman and minority students working in PI’s lab, with support from AFOSR and NSF.

Collaboration with other scientists

During the last couple of years, the P.I. has been in closed contact/collaboration with theorists and applied mathematicians including Prof. Mark Ablowitz at Univ. of Colorado, Prof. D.N. Christodoulides at CREOL, University of Central Florida, Prof. J. Yang at University of Vermont, and Prof. N. K. Efremidis at University of Crete, Greece. Some of them are currently also AFOSR contractors in the nonlinear optics program. The P.I. will continue the collaboration with other contractors and discuss with them about productive plans and future collaboration for the AFOSR projects.

Publications Acknowledged AFOSR Support during 2012-2015:

Book & Book Chapters:

- Z. Chen, and R. Morandotti eds., *Nonlinear Photonics and Novel Phenomena*, Springer Series in Optical Sciences, Vol 171, ISBN 978-1-4614-3537-2 (Springer, 2012).
- Y. Hu, P. Zhang, Z. Chen and G. A. Siviloglo, D. N. Christodoulides, "Generation and control of accelerating Airy beams", in *Nonlinear Photonics and Novel Phenomena*, Vol 171. Z. Chen, and R. Morandotti eds. (Springer, 2012).
- P. Zhang, Cibo Lou, Yi Hu, Sheng Liu, Jianlin Zhao, Jingjun Xu, and Zhigang Chen, "Spatial beam dynamics mediated by hybrid nonlinearity", in *Nonlinear Photonics and Novel Phenomena*, Vol 171. Z. Chen, and R. Morandotti eds. (Springer, 2012).

Referred Journal Actricles:

- P. Zhang, Yi Hu, D. Cannan*, A. Salandrino, T. Li, R. Morandotti, X. Zhang, and Z. Chen, "Generation of linear and nonlinear nonparaxial accelerating beams", *Opt. Lett.*, **37,** 2820 (2012).
- D. Song, C. Lou, L. Tang, Z. Ye, J. Xu and Z. Chen, "Experiments on linear and nonlinear localization of optical vortices in optically-induced photonic lattices", *International Journal of Optic*s, Invited Review Article, Article ID 273857, (2012).
- S. Liu, Y.Hu, P. Zhang, X. Gan, C.Lou, D. Song, J. Zhao, J. Xu, and Z. Chen, "Symmetry-breaking diffraction and dynamical self-trapping in optically induced hexagonal photonic lattices", *Appl. Phys. Lett*. **100**, 061907 (2012).
- Chremmos, Z. Chen, D. N. Christodoulides, and N.K. Efremidis, "Abruptly autofocusing and autodefocusing optical beams with arbitrary caustics", *Phys. Rev. A*, **85**, 023828 (2012).
- S. Liu, Yi Hu, P. Zhang, X. Gan, C. Lou, D. Song, J. Zhao, J. Xu, and Z. Chen, "Tunable self-shifting Bloch modes in anisotropic hexagonal photonic lattices", *Opt. Lett.*, **37,** 2184 (2012).
- Z. Zhang, D. Cannan*, P. Zhang, J. Liu, D.N. Christodoulides and Z. Chen, "Observation of trapping and transporting air-borne particles with a single optical beam", Opt. Express, **20**, 16212 (2012).
- J. Yang, D. Gallardo*, A. Miller* and Z. Chen, "Elimination of transverse instability in stripe solitons by one-dimensional lattices", *Opt. Lett.*, **37,** 1571 (2012).
- Y. Hu, Z. Sun, D. Bongiovanni, D. Song, C. Lou, J. Xu, Z. Chen and R. Morandotti, "Reshaping the trajectory and spectrum of nonlinear Airy beams", Opt. Lett**.**, **37**, 3201 (2012).
- P. Zhang, D. Hernandez*, D. Cannan*, Y. Hu, S. Fardad, S. Huang*, J. Chen, D. N. Christodoulides and Z. Chen, "Rotating beads and bacteria with optical tweezers based on propelling beams", *Biomedical Opt. Express*, **3**, 1892 (2012).
- Z. Chen, M. Segev, D.N. Christodoulides, "Optical spatial solitons: historical overview and recent advances", Invited review paper, Rep. Prog. Phys. **75**, 086401 (2012).
- P. Zhang, Y. Hu, T. Li, D. Cannan*, X. Yin, R. Morandotti, Z. Chen, and X. Zhang, "Nonparaxial Mathieu and Weber Accelerating Beams", Phys. Rev. Lett. **109**, 193901 (2012). (see "Synopsis: Optical Boomerangs", This week in *Physics* — November 19, 2012; "OPN Scatterings: Two New Classes of Accelerating Light Beams", November 19, 2012).
- D. Chremmos, Z. Chen, D. N. Christodoulides and N. K. Efremidis, "Bessel-like optical beams with arbitrary trajectories", Opt. Lett**.** **37**, 5003 (2012).
- P. Zhang, D. Hernandez*, D. Cannan*, Y. Hu, S. Fardad, S. Huang*, J. Chen, D. N. Christodoulides and Z. Chen, "Rotating Beads and Bacteria with Moiré-based Optical Tweezers", *Opt. & Photonics News*, December issue ("Optics in 2012").

- J. Zhao, P. Zhang, D. Deng, J. Liu, Y. Gao, I. D. Chremmos, N. K. Efremidis, D. N. Christodoulides, and Z. Chen, "Observation of self-accelerating Bessel-like optical beams along arbitrary trajectories," *Opt. Lett*. **38**, 498-500 (2013).
- Y. Hu, M. Li, D. Bongiovanni, M. Clerici, J. Yao, Z. Chen, J. Azaña, and R. Morandotti, "Spectrum to distance mapping via nonlinear Airy pulses," *Opt. Lett*. **38**, 380-382 (2013).
- Z. Zhang, P. Zhang, M. Mills, Z. Chen, D. N. Christodoulides, and J. Liu, "Trapping aerosols with optical bottle arrays generated through a superposition of multiple Airy beams," *Chin. Opt. Lett*. **11**, 033502 (2013).
- M. C. Rechtsman, Y. Plotnik, J. M. Zeuner, D. Song, Z. Chen, A. Szameit and M. Segev, "Topological Creation and Destruction of Edge States in Photonic Graphene", *Phys. Rev. Lett*., **111**, 103901 (2013).
- R. Driben, Y. Hu, Z. Chen, B. A. Malomed, and R. Morandotti, "Inversion and tight focusing of Airy pulses under the action of third-order dispersion," *Opt. Lett*. **38**, 2499-2501 (2013).
- Y. Hu, D. Bongiovanni, Z. Chen and R. Morandotti, "Periodic self-accelerating beams by combined phase and amplitude modulation in the Fourier space," *Opt. Lett*. **38**, 3387-3389 (2013).
- S. Fardad, M. S. Mills, P. Zhang. W. Man, Z. Chen, and D.N. Christodoulides, "Interactions between self-channeled optical beams in soft-matter systems with artificial nonlinearities", *Opt. Lett*. **38**, 3585 (2013).
- D. Deng, Y. Gao, J. Zhao, P. Zhang, and Z. Chen, "Three-dimensional nonparaxial beams in parabolic rotational coordinates," *Opt. Lett*. **38**, 3934-3936 (2013).
- J. Zhao, P. Zhang, D. Deng, C. Lou, D. Song, J. Liu, and Z. Chen, "Self-accelerating and self-breathing Bessel-like beams along arbitrary trajectories," *Chin. Opt. Lett*. **11**, 110701 (2013).
- Y. Hu, D. Bongiovanni, Z. Chen and R. Morandotti, "Multi-path multi-component self-accelerating beams through spectrum-engineered position mapping", *Phys. Rev. A*, **88**, 043809 (2013).
- W. Man, S. Fardad, Z. Zhang, J. Prakash, M. Lau*, P. Zhang, M. Heinrich, D. N. Christodoulides, and Z. Chen, "Engineered optical nonlinearities and enhanced light transmission in soft-matter systems with tunable polarizabilities", *Phys. Rev. Lett*., **111**, 218302 (2013).
- Z. Zhang, Z. Ye, D. Song, P. Zhang, Z. Chen, "Repositioning and steering laser beam power via coherent combination of multiple Airy beams", *Appl. Opt*. **52**, 8512 (2013).
- Y. Plotnik, M. C. Rechtsman, D. Song, M. Heinrich, J. M. Zeuner, S. Nolte, N. Malkova, J. Xu, A. Szameit, Z. Chen, and M. Segev, "Observation of unconventional edges states in photonic graphene", *Nature Material*, **13**, 57 (2014) (published online: 10 November 2013 | doi:10.1038/nmat3783)
- X. Qi, K.G. Makris, R. El-Ganainy, P. Zhang, J. Bai, D. N. Christodoulides, and Z. Chen, "Observation of accelerating Wannier–Stark beams in optically induced photonic lattices," *Opt. Lett*. **39**, 1065-1068 (2014).
- K. G. Makris, I. Kaminer, R. El-Ganainy, N. K. Efremidis, Z. Chen, M. Segev, and D. N. Christodoulides, "Accelerating diffraction-free beams in photonic lattices," *Opt. Lett*. **39**, 2129-2132 (2014).
- Y. Liang, Y. Hu, Z. Ye, D. Song, C. Lou, X. Zhang, J. Xu, R. Morandotti, and Z. Chen, "Dynamical 2D deformed Airy beams with arbitrary angles between two wings", *J Opt Soc Am A* **31**(7):1468-72 (2014).
- S. Fardad, A. Salandrino, M. Heinrich, P. Zhang, Z. Chen and D. N. Christodoulides, "Plasmonic Resonant Solitons in Metallic Nanosuspensions", *Nano Letters* **14,** 2498–2504 (2014).
- V. Smith, B. Leung, P. Cala, Z. Chen, and W. Man, "Giant tunable self-defocusing nonlinearity and dark soliton attraction observed in m-cresol/nylon thermal solutions," *Opt. Mater. Express* **4**, 1807-1812 (2014)

- Y. Gao, D. Song, S. Chu, Z. Chen, “Artificial Graphene and Related Photonic Lattices Generated With a Simple Method”, *IEEE Photonics Journal*, accepted (2014).
- Y. Hu, A. Tehranchi, S. Wabnitz, R. Kashyap, Z. Chen, and R. Morandotti, “Improved Intra-Pulse Raman Scattering Control via Asymmetric Airy Pulses”, *Phys. Rev. Lett*. 114， 073901 (2015).
- V.Paltoglou, Z. Chen, and N. K. Efremidis, “Composite multi-vortex diffraction-free beams and van Hove singularities in honeycomb lattices”, *Opt. Lett*. **40**, 1037 (2015).
- S. Xia, D. Song, Y. Zong, L. Tang, and Z. Chen, "Observation of self-trapping and rotation of higher-band gap solitons in two-dimensional photonic lattices", *Opt. Express*, **23**, 4397-4405 (2015).
- D. Song, V. Paltoglou, S. Liu, Y. Zhu, D. Gallardo, L. Tang, J. Xu, M. Ablowitz, N. K. Efremidis, and Z. Chen, “Unveiling pseudospin and angular momentum in photonic graphene”, *Nature Communications,* **6**, Article number: 6272 (2015) doi:10.1038/ncomms7272

1.

1. Report Type

Final Report

Primary Contact E-mail

Contact email if there is a problem with the report.

zhigang@sfsu.edu

Primary Contact Phone Number

Contact phone number if there is a problem with the report

4153383876

Organization / Institution name

San Francisco State Univ

Grant/Contract Title

The full title of the funded effort.

Light Control and Image Transmission through Photonic Lattices with Engineered Coupling

Grant/Contract Number

AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-12-1-0111

Principal Investigator Name

The full name of the principal investigator on the grant or contract.

Zhigang Chen

Program Manager

The AFOSR Program Manager currently assigned to the award

Arje Nachman

Reporting Period Start Date

04/15/2012

Reporting Period End Date

03/31/2015

Abstract

The objective of this project is to develop research programs in photonic lattices that are at the frontier of nonlinear optics/photonics for fundamental understandings in scientific knowledge as well as for possible applications of direct interest to the Air Force. The proposed studies include mainly beam control in engineered photonic lattices, Tamm and Shockley-like edge states and topological surface states in 2D honey-comb lattices ("photonic graphene"), and light localization and transport in disordered lattices. Apart from these proposed studies, the project made additional efforts on design and control of self-accelerating beams and nonlinear enhanced transmission in synthetic colloidal nanosuspensions. These studies will advance the knowledge in several interdisciplinary areas such as nonlinear optics, condensed matter physics, atmospheric sciences, and will also have many application potentials.

Distribution Statement

This is block 12 on the SF298 form.

Explanation for Distribution Statement

If this is not approved for public release, please provide a short explanation. E.g., contains proprietary information.

SF298 Form

Please attach your SF298 form. A blank SF298 can be found here. Please do not password protect or secure the PDF The maximum file size for an SF298 is 50MB.

AF_SF298_2015.pdf

Upload the Report Document. File must be a PDF. Please do not password protect or secure the PDF . The maximum file size for the Report Document is 50MB.

AFOSR_finalReport_March2015.pdf

Upload a Report Document, if any. The maximum file size for the Report Document is 50MB.

Archival Publications (published) during reporting period:

See the list in the report

Changes in research objectives (if any):

Change in AFOSR Program Manager, if any:

Extensions granted or milestones slipped, if any:

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

E-mail user

Apr 23, 2015 00:51:30 Success: Email Sent to: zhigang@sfsu.edu